Designing variable speed small hydro turbine with doubly fed induction generator (DFIG)

IMRAN HASEEB, [a,b] ABDUL BASIT, [a] RAHEEL KHAN, [a,b] MUHAMMAD ASIF [b]
Electrical department
[a]CECOS University of IT and Emerging Sciences
Hayatabad Phase 6 Peshawar PAKISTAN
[b]Qurtuba University of Science & IT, D.I.Khan, KPK, PAKISTAN

Imran.ghilzai@gmail.com

Abstract: - Mostly the small hydro power plants built on a run of river, they are without any water storage capability. When enough water is available in the river then the power can be generated. In this research paper I discussed the maximum power extracted through run off river plant using doubly fed induction generator. Now a day for variable speed turbines doubly fed induction generator is the most suitable machine to extract electrical power from the energy source. In this research paper I proposed a study of variable speed turbine on a run off river plant using doubly fed induction generator. Usually electrical power is extracted from variable speed small hydro turbine through synchronous or induction generator but in both cases voltage magnitude and frequency change with changing of discharge. In proposed research paper I stabilize frequency and magnitude of voltage by doubly fed induction generator.

The entire model has been verified by simulation using MATLAB/simulation environment under the various situation, such as discharge values and different reference reactive power on rotor side converter and also on different reference reactive power on grid side converter. From the simulation results and investigation we can say that p doubly fed induction generator model can extract maximum power from run off river without affecting the voltage magnitude and frequency and reactive power control between grid and DFIG.

Key-Words: - DFIG, Renewable energy, Hydal, Grid.

1 Introduction

Nowadays the major problem the world had to face is the power shortage. For the growth of the economy of any country electric power plays an important role [1]. As according to the report of international energy agency (IEA)in the year 2030 16% (approximately 1.3 billion) peoples will not receive electric power[2,3].As the demand increases every day so generation is also increasing by conventional resources but the world is facing different problems like greenhouse gasses and other toxic materials. Renewable energy is the best solution to solve these all issues. In the last few decades because of pollution free and increasing cost of oil and gasses use of use of renewable power increases [4]. Among all renewable resources wind, hydro and solar energy are more popular because these resources can give bulk power [5, 6]. But the availability of solar and wind energy is intermittent, therefore we cannot get continuous power from these resources [7]. For continuous renewable energy resources, the most suitable and continuous source of energy is the hydro energy [8]. In Pakistan potential of hydro power is 60,000 MW but we convert only 11% hydro power to electric power and [9]. Hydropower can be classified on the bases of capacity as:

1. pico (< 10kW)
2. micro (11kW – 500 kW)
3. mini (501kW – 2000 kW)
4. large (> 2000 kW)

First three types Pico, micro and mini are collectively called small hydro-power and this classification may differ from country to country [8,10]. In many countries small hydro generation worked for the rural electrification as a distributed generation [10,33]. Usually Small hydro plants are installed on the run-of-river category [11]. Small hydro plants can be work as standalone or we can integrate with the grid. The peak or surge loads cannot be exceeded if the small hydro plant is working as a standalone. The stream available head, flow rate and discharge of water determined the output power of the generator so the peak or surge loads should be equal to the available output power of the generator [8]. To generate enough power for all household needs, this type of system needs to be sized relatively large [13, 14]. If we integrate the squirrel cage induction generator to the grid then due to fluctuation in the discharge of water, fluctuation in voltage and frequency are directly transferred to the grid. Also we can't control the active and reactive power, which typically is an important control parameter to regulate the frequency and the voltage [15]. So we need power electronics to interface between the Hydro turbine and the grid. After using the power electronics, characteristics of hydro turbine changed from energy source to the active power source. If the fluctuation of speed is in the narrow range then we can use the squirrel cage induction generator and can integrate with the grid but the efficiency is low and less control of power flow. Another major problem with squirrel cage induction generator is that power system is the reactive power source so we required to compensate reactive power to maintain line voltage and protect the system from overload [34]. If the short circuit ratio of the grid is low then during some fault condition then induction generator can't control the speed and power factor and cannot assist in the stability of the grid [35].

Early in the 1980s, that was just the soft starter to use power electronic devices with variable speed power resources like wind and hydro. Initially it was only used to connect the connect the squirrel cage induction generator with grid and we only used simple thyristor to control the fluctuation but they did not carry continuous power [16][17]. After ten years in the 1990s the more advanced diodes with a chopper is used with the wound rotor induction generator. Here the main purpose of power electronics is to control the rotor resistance of the wound rotor induction generator. [16][18].

After power electronics have been matured, the doubly fed induction generator (DFIG) is becoming the most vital part of variable speed power generation [19] [20]. The doubly fed induction machine (DFIM) is also known as the wound-rotor or slip-ring induction machine, this is also an induction machine with both stator and rotor windings. Now a days DFIG is mostly used as a generator, especially used in variable-speed power sources and a back to back converter connected between the rotor and grid [21]. A schematic diagram of a DFIG-based hydro energy generation system is shown in Fig.1

Currently, up to 50% of the wind energy market using DFIG. [22]. Compared to fixed speed induction generators, DFIG-based wind turbines gives many advantages such as variable speed operation of the turbine and four-quadrant active and reactive power capabilities.

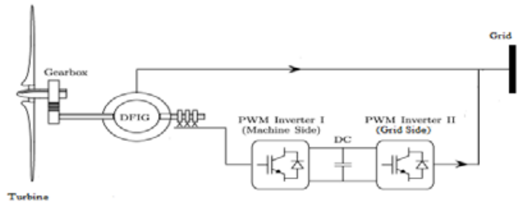


Fig.1 Schematic of DFIG based hydro turbine system

Cost of converter and power loss is also reduced when we compare DFIG with the fully fed induction generator [23] [24]. DFIG requires low power Converters rated at about 30% of generator power being also able to generate active and reactive power and operate in all four quadrants [25]. During fault condition and the short circuit of the grid is low then DFIG can assist the grid stability because of speed and power factor controlled model in doubly fed induction generator.

Nowadays DFIG is commonly used in wind generation. Similarly can also be used in a small hydro power generation can improve the efficiency of power generation. Some topology of the wind turbine can be adopted for small-hydro turbine generation. As the discharge of water is not constant in the run off river plant and flow of water varies all the day so it affects the rotational speed of turbine but it gives higher efficiency in variable speed operation [26]. For safe and reliable operation we required to develop a control for DFIG with variable speed hydro turbine [27]. To control the frequency of the machine we need to control the active power and for voltage we need to control the reactive power [28]. So by controlling these two variables we can integrate all our small hydro plants with the grid and increase of power generation.

2 Mechanical power output

Hydro power through penstock converted into mechanical power by Turbine. Max power output can be extracted from a hydro turbine by Hill chart. . Every point on hill charts gives four features including speed of the turbine, water flow, efficiency or effectiveness and gate openings. To draw a Hill Charts, gate opening remains fixed while changing the speed. Different speed related to point of flow rates or we take power at a different point. For fixed gate openings, turbine speeds, flow rates and the productivity are examined. We repeated this process for different gate opening angles and the graph made after mentioning the points refer to as Hill Chart in figure 2.

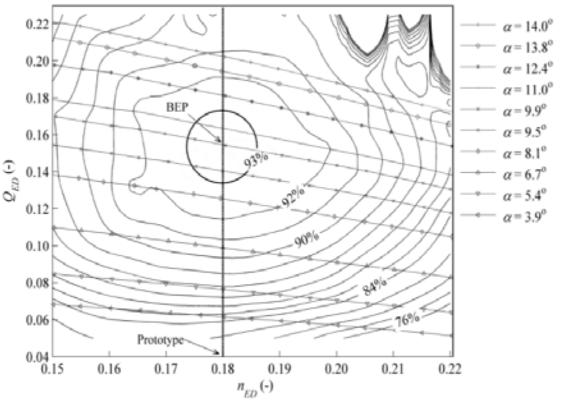


Figure 2: hill chart for different gate opening

Where Q_{ED} is discharge on Y-axis and $n_{ED}$is the speed on X-axis. Where α is the different gate opening angle.

By equation mechanical power obtained from the hydro turbine is

P= ηQgH

Here η is the turbine efficiency,Q is the discharge of water,G is the gravity and H is the available head

3 Mathematical modeling of DFIG

The constant steady state equations for voltages, fluxes and currents are obtained by the Kirchoff's voltage laws[28], stators and rotors voltages equations are

$$V_s = R_s I_s + j\omega_s \lambda_s \quad (1)$$

$$V_r = R_r I_r + j\omega_r \lambda_r \quad (2)$$

$$\lambda_s = L_s I_s + L_m I_r \quad (3)$$

$$\lambda_r = L_r I_r + L_m I_s \quad (4)$$

$$I_s = \lambda_s \frac{1}{\sigma L_s} - \lambda_r \frac{L_m}{\sigma L_s L_r} \quad (5)$$

$$I_r = \lambda_r \frac{1}{\sigma L_r} - \lambda_s \frac{L_m}{\sigma L_s L_r} \quad (6)$$

Here σ refers to the leakage reactance which equal to $1 - \frac{L_m^2}{L_s L_r}$.

3.1 Vector control of rotor side converter

Three phase voltage, current and flux of induction machine are represented by space vector. In vector control method we control these quantities by regulating the magnitude and phase angle [32]. By the integrating with both stator and rotor fluxes torque is generated. Actual power can be controlled by controlling the stator and rotor fluxes. Access to only stator side is given in squirrel cage induction machine while both rotor and stator sides are accessible in DFIG. Stator winding of DFIG is connected to grid and rotor side is connected to the grid by back to back converter to inject voltage and current of required magnitude and frequency to keep the stator voltage constant. For better control, three phase quantities convert into two phase by Clark and Park transformation [33]. In two-phase (DQ transformation) we control both phases d and q separately. On rotor side we aligned d axis flux with the stator flux so q axis flux and d axis voltage become zero so we can control torque and active power by q axis current and reactive power by q axis current[38].

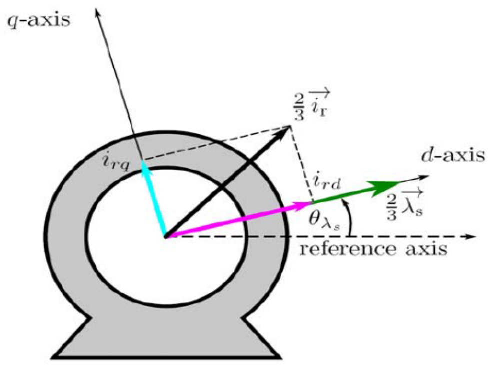


Figure 4 Vector representation in DFIG

We set the reference rotor currents idr according to reactive power need and the reference value is compared to calculated d axis current and internal PI loops generating d axis rotor voltages applied to rotor side converters Rotor voltage dynamics are [29]

$$v_{dr} = R_r i_{dr} + \frac{d}{dt}\lambda_{dr} - \omega_r \lambda_{qr} \quad (7)$$

$$v_{qr} = R_r i_{qr} + \frac{d}{dt}\lambda_{qr} + \omega_r \lambda_{dr} \quad (8)$$

Electromagnetic Torque in dq axis

$$T_e = \frac{3}{2} p_p (i_{dr}\lambda_{qs} - i_{qr}\lambda_{ds}) \quad (9)$$

By aligning the stator flux with direct axis stator flux [30]. So torque equation will be

$$T_e = \frac{3}{2} p_p (i_{qr} \lambda ds) \tag{10}$$

$$T_e = \frac{3}{2} p_p \left(\frac{Lm\lambda ds}{Ls}\right) iqr \tag{11}$$

Stator's active powers in terms of dq axis

$$P_s = \left(\frac{M V_s}{L_s}\right) I_{qr} \tag{12}$$

Stator's reactive powers in terms of dq axis

$$q_s = \frac{3}{2}\left(v_{qs} i_{ds} - v_{ds} i_{qs}\right) \tag{13}$$

As stator direct flux is aligned with stator flux so v_{ds} will be zero so

$$q_s = -\frac{3}{2} v_{qs} i_{ds} \tag{14}$$

3.2 Vector control of grid side converter

The main purpose of grid side converter is to main bus voltage across the DC link capacitor. Power flow between back to back converter (grid side converter and rotor side converter) depends upon bus voltage [31].

$$p_g - p_r = \frac{1}{2} C_{DC} \frac{d}{dt} V_{DC}^2 \tag{15}$$

Active power across grid side converter can be written as

$$p_g = \frac{3}{2}\left(v_{dg} i_{dg} + v_{qg} i_{qg}\right) \tag{16}$$

On grid side converter direct grid voltage is aligned with stator voltage so

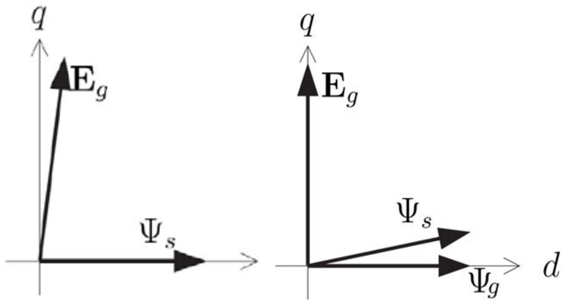


Figure 5 Grid voltage and fux in DQ axis

Grid active power will be

$$p_g = \frac{3}{2}\left(v_{dg} i_{dg}\right) \tag{17}$$

Grid side reactive power

$$Q_g = \frac{3}{2}\left(v_{qg} i_{dg} - v_{dg} i_{qg}\right) \tag{18}$$

$$Q_g = \frac{3}{2}\left(-v_{dg} i_{qg}\right) \tag{19}$$

4 PI controller for DFIG

On the basis of power references, rotor speed reference is produced by optimal speed model. It is used to compute electromagnetic torques utilized for generating. Current references for quadrature axis rotor currents.

The error between both reference speed and measured speed can be decreased by appropriate proportional and integral gains.

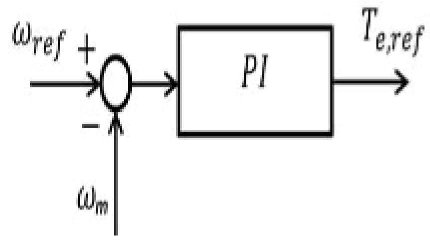


Figure 6 PI control for speed

$$G(s) = \frac{P}{Js} \tag{20}$$

$$R(s) = kp + k_i/s \tag{21}$$

The close loops transferring functions

$$H(s) = \frac{R(s)G(s)}{1+R(s)G(s)} \tag{22}$$

$$H(s) = \frac{k_p s + k_i}{j/p s^2 + k_p s + k_i} \tag{23}$$

Compare the transfer function with equation

$$F(s) = \frac{\omega_c^2}{s^2 + 2\varepsilon\omega_c s + \omega_c^2} \tag{24}$$

So we get

$$k_p = \frac{J}{p} \varepsilon \omega_n \tag{25}$$

$$k_i = \omega_n^2 \tag{26}$$

Similarly tuned proportional and integral gain for i_{dr} and i_{qr} for the rotor side converter.

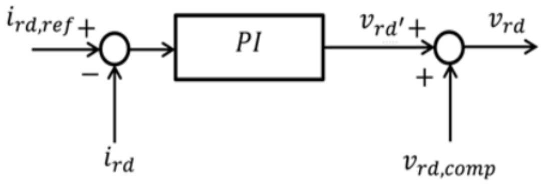


Figure 7 PI control for Idr

On the grid side converter we tuned PI gains for bus voltage and for i_{dg} and i_{qg}. Block diagrams of

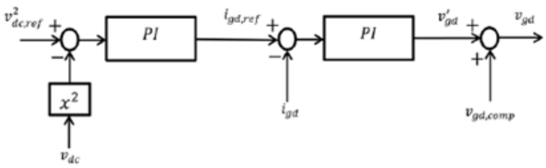


Figure 8 PI control for grid side converter

5 Simulation and results

Simulation of the proposed DFIG-based generation system was carried out using Simulink/Matlab and Fig. 7 shows the schematic diagram of the DFIG base small hydro plant. The DFIG rated power is 2 MW. The nominal dc link voltage is 1050 V and the dc link capacitance is 80 mF. Switching harmonics are generated by the converter which is absorbed by the RC filter. The main objective of rotor side converter is to control active and reactive power on basis of the vector control scheme and main objective of grid side converter is to maintain constant DC link voltage. It is controlled using a similar method as the dc voltage controller in a VSC Transmission system [36] and the shunt converter in a UPFC [37].

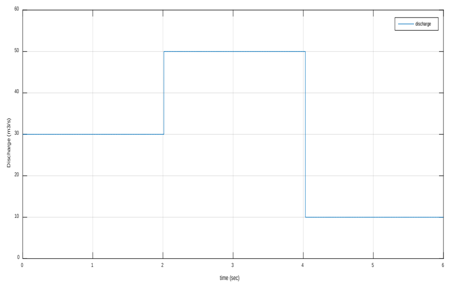


Figure 1. Discharge of Water in Run-Off River Plant

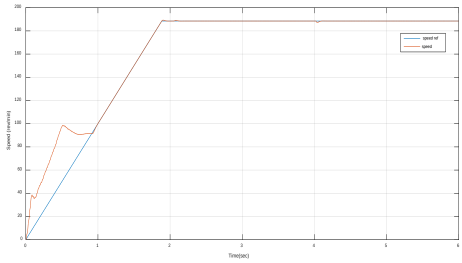


Figure 2. Speed of Doubly Fed Induction Generator

Figure 1 represents water discharge in run-off river plant located in Battagram (KPK), Pakistan.The range of water discharge at this site is between 10 m/s to 50m/s throughout the year. In this simulation after each 2 sec discharge is changing. Figure 2 represents the machine's speed that follows the references speed which is 188 m/s. When speed reached at 0.8 sec machine's speed track the reference speed. The speed of the machine is not changing with the change of discharge after each 2 sec.

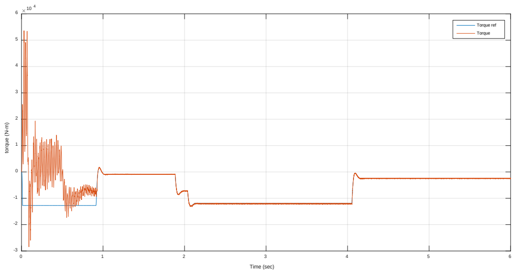


Figure 3. Torque generated in DFIG

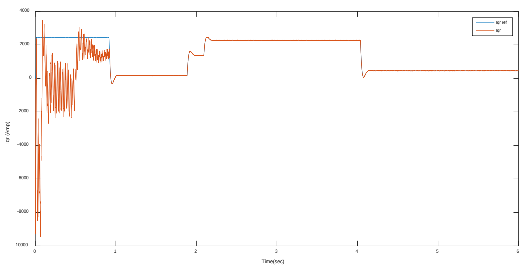


Figure 4. Rotor Quadrature Current

Figure 3 represents the torque of the generator which is increased with increasing the discharge at 2 sec and again when we discharge is decreasing at 4 sec so torque is also decreasing. As DFIG is working as a generator so torque is negative.

Figure 4 represents the rotor quadrature current Iqr which is increased with increasing water discharge and decrease with the decrease of discharge of water.

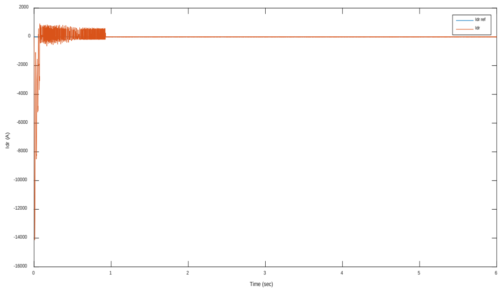


Figure 5. Rotor Direct Current

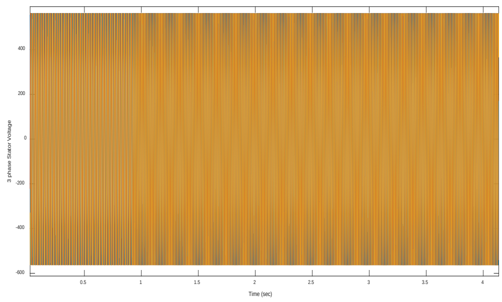


Figure 6. Three Phase Stator Voltages

Figure 5 represents the rotor direct current Idr, as reactive power is zero so Idr remains zero all the time. Figure 6 represents three phase stator voltage which shows that it gives constant three-phase voltage.

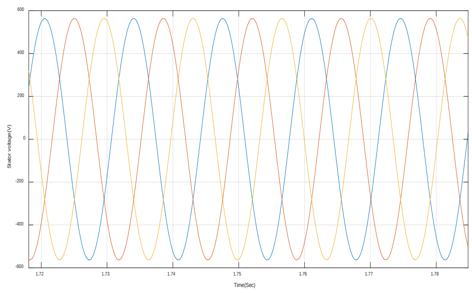


Figure 7. Three Phase Stator Voltages

Figure 7 represents the three-phase stator voltage between 1.72 sec to 1.79 sec. This figure clearly shows that three phase voltage magnitude and frequency remain constant.

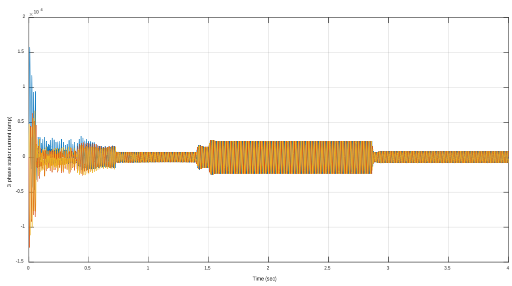


Figure 8. Three Phase Stator Current

Figure 8 represents the three-phase stator current which increases with the water's discharge and decrease with the water's discharge.

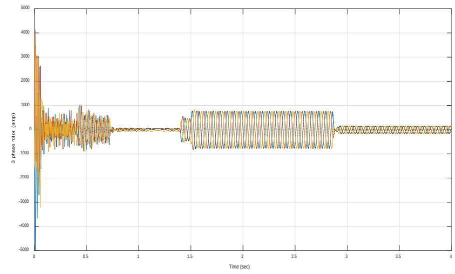


Figure 9. Three Phase Rotor Current

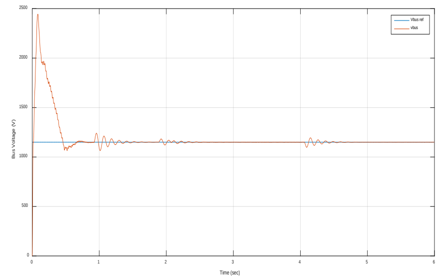


Figure 10. Bus Voltage

Figure 9 represent the three-phase rotor current which is change with the change in water's discharge. With the increase of discharge three phase rotor current also increases and with decrease its also decrease.

Figure 10 represent the bus voltage on the grid side. Bus voltage is tracking the reference bus voltage 1050 v.

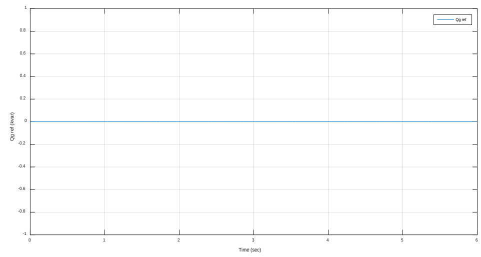


Figure 11. Grid Reactance Power Reference

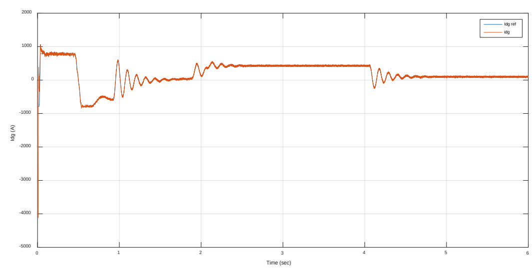


Figure 12. Grid Direct current

Figure 11 represents the reference reactance power.in this proposed paper reactive power is zero but we can change the reference reactive power according to grid codes. Figure 12 represents the direct grid current. Idr is tracking the reference value which is change with the changing water's discharge.

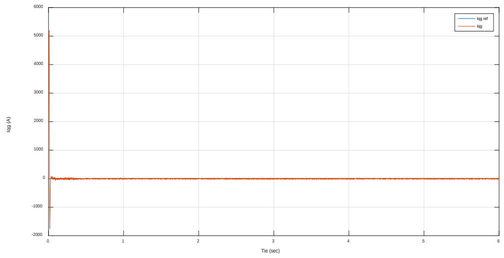


Figure 13. Quadrature Grid Current

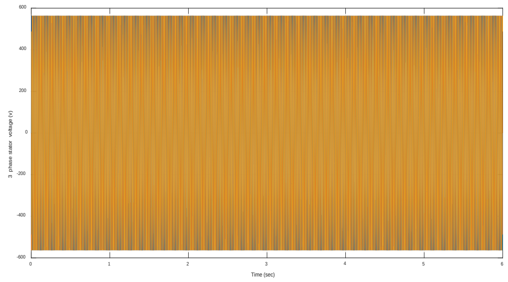
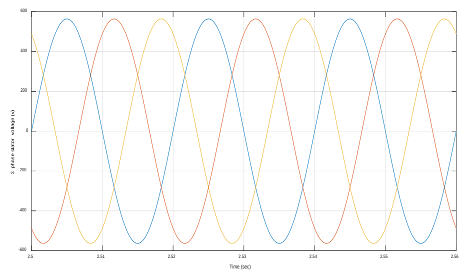


Figure 14. Three Phase grid Voltages

Figure 13 represents the quadrature grid current which is also zero because reference reactive power is zero. Figure 14 again represents the three phase grid voltage which remains constant. Change in discharge or reactive power is not affecting the voltage magnitude or frequency.

Figure 15 also represent the three-phase stator voltage between 2.50 sec to 2.56 sec. After zooming the three-phase grid voltage its clearly shows that magnitude and frequency are constant.



Figur e 15. Three Phase Stator Voltages

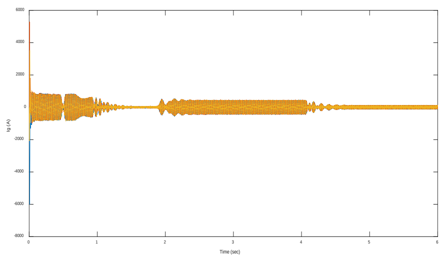


Figure 16. Three Phase grid Current

Figure 16 represents the three-phase grid current which is increased or decreased with water's discharge.

4 Conclusion

From figure 2 it is clear that generator speed is constant and tracking the reference speed at 0.8 sec. As discharge is not constant but speed remains constant and from figure 6 and 14 three phase stator voltage and three phase grid voltage is also constant but rotor current increase with the increase of water discharge. In figure 10 bus voltage track the reference bus voltage at 1050 v and it remains constant all the time.

In a third world country like Pakistan where the gap between power demand and supply is large. We can increase our power supply by integrating all our wind solar and hydro plant to the grid and reduce the supply and demand gap. DFIG is the best solution to integrate variable speed power sources

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